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REFERENCES

[1] J. J. Egli, "Radio propagation above 40 MC over irregular terrain," *Proc. IRE*, vol. 45, pp. 1383–1391, 1957.
[2] J. P. Murphy, "Statistical propagation model for irregular terrain paths between transportable and mobile antennas," in *AGARD Conf. Proc.*, vol. CP 70-71, pp. 49.1–49.20, 1971.
[3] "Recommendations and reports of the CCIR, 1978," vol. 5, Rep. 567-1, presented at the XIVth Plenary Assembly, Kyoto, Japan, p. 167, 1978.
[4] "Atlas of ground-wave propagation curves for frequencies between 30 *Mc*/s and 300 *Mc*/s," CCIR, published by the ITU, Geneva, 1955.
[5] *Reference Data for Radio Engineers*, 5th Ed. New York: Howard Sams, 1969.

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Extraction of Multipath Parameters from Swept Measurements on a Line-of-Sight Path

JØRGEN SANDBERG, MEMBER, IEEE

Abstract—**A computerized method of obtaining the multipath parameters from swept measurements is described, and some results are discussed. The accuracy of the multipath parameters determined is about ±0.3 ns in delay and ±0.1 in amplitude. The time variation of the propagation medium during the 331-ms sweep time is included in the multipath model. This has a significant impact on the analysis and on the results obtained.**

I. INTRODUCTION

SIGNIFICANT variations have been observed in the quality of the received signal in terrestrial line-of-sight radio communication systems. The variations of the transmission quality are due to the inevitable anomalies of the radio wave propagation. These anomalies are caused by precipitation or by nonstandard refractive conditions; the latter are exemplified by multipath propagation or general ray bending.

The path followed by the radio waves from the transmitter to the receiver is determined by the height of, and the distance between, the antennas and by the radio refractive index of the troposphere. The references [1]–[3] describe the radio wave propagation by means of geometrical optics. This approach is commonly followed and is also adopted in this paper. (The author is aware of the more exact theories that have been developed lately by Felsen *et al.* in [4]–[6], where the electromagnetic fields are confined in space and time instead of being approximated by infinite plane waves, but these theories were not used for the analysis of the data measured, because they were found to be too complicated.)

Multipath propagation at microwave frequencies is characterized by deep frequency selective fadings in contrast to the flat fadings caused by precipitation. This difference serves to distinguish multipath events from precipitation-caused fadings. The deep selective fadings occur because a) the number of propagation paths is small (being from two to five), b) no one path has a dominating signal, and c) the lengths of the individual paths differ by at least a few tenths of a meter, corresponding to relative delays of few nanoseconds or more.

The multipath parameters unambiguously describe a multipath propagation event, because they are defined in terms of a) the number N of propagation paths, b) the relative amplitudes a_i, $i = 1, \cdots, N$, and c) the relative delays τ_i, $i = 1, \cdots, N$, of the signals following the individual paths $i = 1, \cdots, N$. The amplitude terms and the delay terms are related to the amplitude and the propagation time prevailing during normal one-path propagation. That is, when normal one-path propagation occurs, the multipath parameters become $N = 1$, $a_1 = 1$, and $\tau_1 = 0$.

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Two methods of measuring the multipath parameters exist. One method is to transmit a pulse that is about one order of magnitude narrower than the smallest delay expected, and measure the amplitude and the delay of each received pulse. This method is equivalent to measuring the impulse response of the propagation medium and yields the multipath parameters directly. Another method is to determine the complex transfer function of the propagation medium by measuring the amplitude and phase characteristics. The multipath parameters are then obtained by inspecting the impulse response, which is found by Fourier transforming the complex transfer function.

The delays τ_i for microwave line-of-sight links may be less than 1 ns. Therefore, the bandwidth necessary to carry out the measurements described above is several gigahertz, which is not feasible in practice. Consequently, pulse durations of about 1 ns are normally used in the first method, and sweep bandwidths of about 1 GHz are used in the second method. The result is that the impulse responses, which are measured directly in the first method and obtained by a Fourier technique in the second method, become a sum of overlapping pulses, i.e., in both methods the multipath parameters cannot be found by a simple inspection of the impluse reponse but are found in an iterative process using a simulator. In the first method the simulator synthesizes the impulse response based on the set of multipath parameters that are given as input, while the second method it is the amplitude characteristic that is synthesized. In the iterative process the multipath parameters used as input to the simulator are adjusted until the synthesized pattern matches the measured pattern.

The impulse-response-measuring method has been used by DeLange [7] using a pulse length of 3 ns and a carrier frequency of 4 GHz. The amplitude values (a_i) were not recorded, but delays (τ_i) ranging from less than 1 ns to about 7 ns were observed. This method has also been used by Bernardini *et al.* [8].

The amplitude-and-phase-measuring method has been used by Crawford and Jakes [9]. They measured the amplitude characteristic in a 450-MHz band centered at 3.950 GHz. The synthesis of the complicated frequency sweep patterns was performed on an analog computer, which combined four signal components, three of which were variable in amplitude and delay. The synthesized and measured patterns were displayed on a cathode ray tube, and the amplitudes and delays were varied until the two patterns agreed satisfactorily. In most cases the amplitudes of the first two paths were nearly equal and had a mutual delay difference of about 1 ns, while the amplitudes of the remaining two components were one order of magnitude less. The delays of the small components were about 5–10 ns.

Kaylor [10] carried out a sweep experiment similar to that described above. He found that in the majority of the multipath propagation cases about five components were required. In a single case involving a 40-dB fading it was estimated that seven components were necessary before a satisfactory match of the measured and synthesized patterns could be obtained.

A frequency sweep experiment has been carried out by Meadows *et al.* [11], within the frequency range 3.6–4.1 GHz. A Fourier technique was used for extracting the multipath parameters. The resolution obtained was about 4 ns, and delays ranging from about 2 to 10 ns were observed.

The British Post Office Research Department in England has run extensive experiments on radiowave propagation at frequencies above 10 GHz, with special attention to multipath transmission [12], [13]. The sweep bandwidth was 500 MHz in all of these experiments, and the fading patterns were analyzed manually on a simulator. Delays between about 0.1 and 9 ns were found.

It is a general observation that multipath propagation occurs during clear summer nights, when temperature inversions and associated meteorological effects produce tropospheric layers with excessively negative refraction gradients. Ruthroff [14] established a model of the troposphere with a single refracting layer. Depending on the distance between the transmitter and the receiver, and the following parameters for the elevated refracting layer—the height, the thickness, and the index of refraction—up to three propagation paths are shown to be possible.

The experiment described in this paper has been designed by the Electromagnetics Institute of the Technical University of Denmark, and the equipment has been developed in cooperation with the Danish Post and Telegraph Administration. These two bodies run the experiment jointly, and it is based on the amplitude-and-phase-measuring method. The way in which the patterns measured are analysed has been shaped by on-the-job experience.

II. DESCRIPTION OF THE MEASUREMENT

The measuring equipment is installed on a 75-km path that runs south-west from the center of Copenhagen. The transmitter is outside Copenhagen and the antenna is mounted on a tower 25 m above the ground and 165 m above the sea surface. The receiver antenna is mounted on a tower 50 m above the top of the surrounding buildings and 88 m above the sea surface. The propagation path is over an area that is urban as well as rural. The first Fresnel zone is clear, and the terrain roughness (defined as the standard deviation of the terrain elevations at 1-km intervals) is 21 m.

The transmitter emits a frequency swept carrier, which is frequency modulated by a 10-MHz sine wave with a modulation index of 0.1. The carrier is swept sinusoidally from 13.5 to 15.0 GHz with a period of 1 s.

The receiver is swept synchronously with the transmitter, and the differential phase, the differential gain, and the logarithm of the received carrier amplitude are digitized as 12-bit and recorded on magnetic tape at every 2.5-MHz interval in the range 13.6425–14.9300 MHz. The measurement sweep duration is therefore 331 ms. The dynamic ranges of the three measured quantities are relative to the normal daytime values: amplitude = +12 dB to –60 dB, differential phase = +180° to –180°, and differential gain = +14 dB to –6 dB.

The antennas of the transmitter and the receiver are 1.28-m uncovered front-feed parabolic reflectors, with a 3-dB beamwidth of about 1°. Since the vast majority of the observed angles of arrival [15], [16] are less than ±0.5° when multipath propagation takes place, the receive antenna will sum up all the signal components without excessively attenuating any of the components. A signal component arriving 0.5° off the axis of the receive antenna will be phase-shifted 0.34° by the antennas assuming that the angle of departure is equal to the angle of arrival. Although small, the antennas nevertheless cause both an attenuation and a phase shift in all signal components that arrive off axis relative to a component that arrives along the antenna axis. When estimating the multipath parameters, these effects are included in the resulting values.

A more detailed description of the equipment has been given in [17]–[19]. Previously, the sweep data have been analyzed to find the statistics of fadings and intermodulation noise [18]–[22].

III. EXTRACTION OF THE MULTIPATH PARAMETERS

The sweep analysis is performed with the aid of a computer. All sweeps in a sequence of sweeps recorded during a period of multipath propagation are analyzed automatically except for one sweep. This single sweep is analyzed by computing the complex transfer function of the medium on the basis of the measured quantities. Subsequently, the transfer function is Fourier transformed to the delay domain, and the absolute value is plotted. This plot is visually inspected, and a first estimate is obtained for the multipath parameters. This estimate constitutes the starting values for a computerized interaction that in turn yields the starting multipath parameters for the same iterative analysis of the other sweeps in the sequence.

The complex transfer function $H(f)$ of the propagation medium is written as

$$H(f) = A_0 e^{-j2\pi f t_0} A(f) e^{j\phi(f)} \tag{1}$$

where A_0 and t_0 are the amplitude and the propagation time, respectively, for normal single-path propagation. The term $A(f)$ exp $\{j\phi(f)\}$ is the deviation from normal single-path propagation and is defined as the normalized complex transfer function;

$$\overline{H(f)} \equiv A(f) e^{j\phi(f)}. \tag{2}$$

The amplitude function $A(f)$ is measured directly. The phase curve $\phi(f)$ is constructed by using the increments of the phase found by relating the demodulated frequency-modulated (FM) signal to the definitions of differential phase and differential gain [23], [24].

Since the receiver has no access to the real time reference of the transmitter, the computed phase $\phi(f)$ differs from the real phase in that it incorporates an additional constant term and a term that is proportional to the frequency. The consequence of this is that each delay τ_i can only be expressed relative to one particular received signal component; the relative delay for this reference component will therefore be $\tau_i = 0$.

Since the measurements are performed at frequencies between 13.6425 and 14.9300 GHz, the normalized complex transfer function $\overline{H(f)}$ of the propagation medium is only known for that frequency band. Therefore the measured complex transfer function $\overline{H_m(f)}$ becomes

$$\overline{H_m(f)} = W(f)\overline{H(f)} \tag{3}$$

$$W(f) = \begin{cases} 1, & 13.6425 \text{ GHz} \leqq f \leqq 14.9300 \text{ GHz} \\ 0, & \text{elsewhere.} \end{cases} \tag{4}$$

Equation (3) implies that the Fourier transformation of the measured complex transfer function $\overline{H_m(f)}$ is equal to the impulse response of the propagation medium convolved with a sin x/x function. The distance between the zero points of the mainlobe of this sin x/x function becomes 1.56 ns, limiting the resolution in delay to about 1.5 ns.

By assuming multipath propagation and invariant propagation conditions, the normalized complex transfer function $\overline{H(f)}$ can be written as

$$\overline{H(f)} = \sum_{i=1}^{N} a_i e^{-j2\pi f \tau_i}, \tag{5}$$

and the Fourier transformation of $\overline{H_m(f)}$ becomes the sum of N individual sin x/x functions, each of which has a maximum value a_i and a delay value τ_i. Fig. 1 shows a set of measured data and the corresponding computed phase for multipath propagation. Fig. 2 is a plot of the absolute value of the Fourier transformation of $\overline{H_m(f)}$ for the data presented in Fig. 1, and it can be seen that there are two sin x/x main lobes, one centered on -0.7 ns and the other centered on $+0.3$ ns. Furthermore, a careful inspection of Fig. 2 reveals an irregular sidelobe around 3.7 ns, which implies that there are three signal components with delays $\tau_1 = 0$, $\tau_2 = (0.7 + 0.3)$ ns $=$ 1.0 ns, and $\tau_3 = (0.7 + 3.7)$ ns $= 4.4$ ns. The amplitudes are estimated to be $a_1 = 0.37$, $a_2 = 0.4$, and $a_3 = 0.05$. This set of estimated multipath parameters is used as the starting values in the computerized iteration.

The Fourier transformation of $\overline{H_m(f)}$ is performed via a discrete Fourier transform technique which yields a periodic time function, the period of which is the reciprocal of the frequency difference between two consecutive samples of $\overline{H_m(f)}$. For the data under consideration the period is $(2.5 \text{ MHz})^{-1} =$ 400 ns, which is at least one order of magnitude greater than the expected delay τ_i. Consequently, the aliasing effects caused by the periodicity are negligible, and even small irregularities in the time spectrum would be attributable to the propagation conditions and not to shortcomings in the time spectrum calculation.

The sidelobes of the sin x/x functions in Fig. 2 are rather confusing but may be reduced by applying a smoother window function $W(f)$ in (3). On the other hand, the drawback of using a smoother window function is the resulting broader main lobe. Experience has showed that the sidelobes of the sin x/x function are preferential to a broader main lobe for the sweep data under consideration.

Figs. 3 and 4 relate to a case of multipath propagation in which the time spectrum is highly irregular, either as a result of there being many signal components or because there are significant time variations in the propagation conditions during the 331-ms sweep duration. Recorded sweep patterns such as those in Fig. 3, and the fact that the time constants involved when inversion layers in the troposphere break-up are less than 1 s [25], indicate that the multipath parameters must vary during a sweep. Therefore, the model introduces multipath parameters that change during a sweep, and since there is a one-to-one relation between time and frequency during a sweep, the time varying multipath parameters can, during a sweep, be presented as frequency dependent parameters. Consequently, the normalized complex transfer function in (5) is modified to

$$\overline{H(f)} = \sum_{i=1}^{N} a_i(f) \exp\{j\phi_i(f)\}. \tag{6}$$

The functional forms of $a_i(f)$ and $\phi_i(f)$ are unknown, but since they describe physical conditions they must be continuous functions. The following series expansions are there-

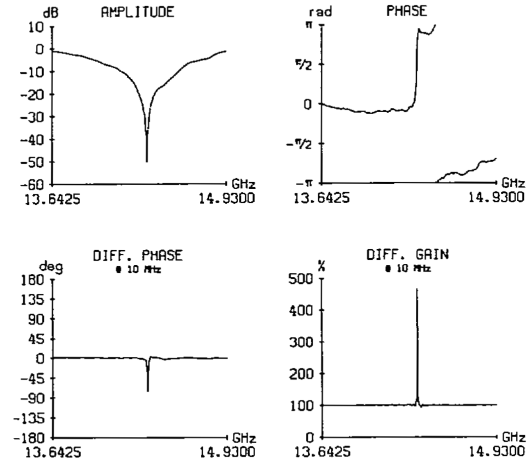

Fig. 1. Set of measured data and computed phase curve.

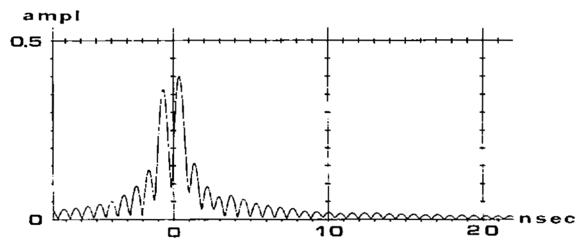

Fig. 2. Absolute value of Fourier transform of $\overline{H_m(f)}$ for date in Fig. 1.

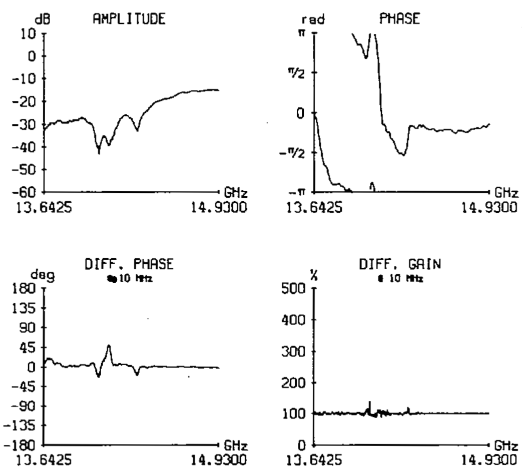

Fig. 3. Set of measured data with involved curves.

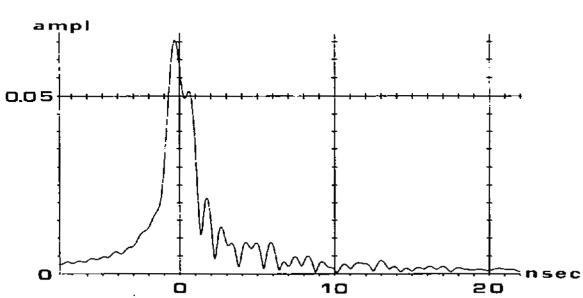

Fig. 4. Highly irregular time spectrum of measured data in Fig. 3.

fore adopted:

$$a_i(f) = a_{0i} + a_{1i}(f - f_0) + a_{2i}(f - f_0)^2 + a_{3i}(f - f_0)^3 \quad (7a)$$

$$\phi_i(f) = -2\pi\{\tau_{0i} + \tau_{1i} f + \tau_{2i}(f - f_0)^2 + \tau_{3i}(f - f_0)^3\}, \quad (7b)$$

where the terms a_{0i} and τ_{1i} are the usual multipath parameters, and by selecting $f_0 = 14.4$ GHz (i.e., roughly the mean sweep frequency) the remaining terms should be small corrections of a_{0i} and τ_{1i}. The term τ_{0i} is a constant phase shift, which may be attributable to water vapor in the troposphere and/or the antenna characteristics. The expansion in (6) is related directly to the multipath parameters, while the expansion in [26] is a general one expressing the deviation from ideal propagation conditions.

The estimation of the multipath parameters is now at the stage of finding the number of propagation paths (N) and the values of the parameters $a_{0i}, \cdots, a_{3i}, \tau_{0i}, \cdots, \tau_{3i}$, for $i = 1, \cdots, N$, so that the amplitude and the differential phase and gain patterns synthesized on the basis of (7a), (7b), and (6) fit the measured patterns. This is done via the computerized iteration which affords a set of starting values to the parameters N, $a_{0i}, \cdots, a_{3i}, \tau_{0i}, \cdots, \tau_{3i}$, for $i = 1, \cdots, N$. For the analysis of the first sweep in a sequence the starting values (N, a_{0i}, and τ_{1i}) are obtained by inspecting the time spectrum, while the starting values of the remaining parameters are set to zero. For each succeeding sweep in the sequence the starting values of the parameters are set equal to the values obtained for the preceding sweep.

The process of iteration includes an optimization procedure which adjusts the variables $N, a_{0i}, \cdots, \tau_{3i}$, for $i = 1, \cdots, N$, until a minimum has been found for the following object functions:

$$F(\bar{x}, f_n) = \frac{\text{amp}_{\text{syn}}(f_n)}{\text{amp}_m(f_n)} - 1, \qquad n = 1, \cdots, 516 \quad (8a)$$

$$G(\bar{x}, f_n) = \text{DPA}_{\text{syn}}(f_n) - \text{DPA}_m(f_n),$$

$$n = 1, \cdots, 516, \quad (8b)$$

where $\bar{x}$ denotes the variables, $\text{amp}_{\text{syn}}(f_n)$ is the synthesized amplitude value at the frequency f_n based on the variables, $\bar{x}$, $\text{amp}_m(f_n)$ is the measured amplitude value at f_n, $\text{DPA}_{\text{syn}}(f_n)$ is the synthesized differential phase value at f_n, and $\text{DPA}_m(f_n)$ is the measured value of the differential phase at f_n. Since the bandwidth of the circuits recording the measured quantities is about 1 kHz, a 55-dB fading will be recorded as a 45-dB fading, assuming two-path propagation and a delay of 1 ns. This effect of the band-limiting circuits is included in the computation of $\text{amp}_{\text{syn}}(f_n)$ and $\text{DPA}_{\text{syn}}(f_n)$.

The optimization procedure tries to adjust the residues $F(\bar{x}, f_n)$ and $G(\bar{x}, f_n)$, $n = 1, \cdots, 516$, such that finally they all have almost the same small value. Since $F(\bar{x}, f_n)$ is equal to the relative error between the synthesized and the measured amplitude patterns, the low levels of the amplitude pattern are fitted with the same accuracy as the high levels. For the differential phase the stress of fitting the patterns is laid on the high levels. The reason for this difference in the object functions of the amplitude and the differential phase is that experience has shown that when the amplitude patterns fit each other, the differential phase patterns also fit each other, except around the frequency of the fading minimum. At this minimum the spike of the synthesized pattern in some cases is positive-going while that of the measured pattern is negative-going (or vise versa), and so $G(x, f_n)$ is tailored to accommodate this difference in sign. In the case of two-path propagation the sign of the spike of the differential phase may be changed without changing the amplitude pattern, by interchanging the amplitude values of the two signal components.

In contrast, it is found that the differential gain patterns always fit whenever the amplitude patterns fit. Consequently, the differential gain pattern does not need to be fitted in the optimization procedure.

As a consequence, the optimization procedure is divided into two steps. In the first step the amplitude patterns are fitted without worrying about the differential phase pattern. In the second step the multipath parameter values found in the first step are examined, and if the differential phase patterns do not fit already, the amplitude values of the main signal components are interchanged, and small adjustments are made to the parameters until a satisfactory fit is obtained for both sets of patterns.

The synthesized amplitude patterns and differential phase patterns are deduced from $\overline{H(f)}$ defined in (6) and (7). If the phase $\phi_i(f)$ changes by a constant of 2π rad at all frequencies, $\overline{H(f)}$ is unchanged, and the same will be true for the object functions. When τ_{1i} changes by $\frac{1}{2}(13.6425 + 14.9300\ \mathrm{GHz})^{-1} = 0.07$ ns, the phase term $2\pi\tau_{1i}f$ changes by 2π rad at the mean frequency and by $2\pi \pm$ (4.5 percent of 2π) at the ends of the sweep band. This means that a) the object functions are quasi-periodic in the delays τ_{1i}, with a period of 0.7 ns; and b) the object functions have local minima for every 0.7 ns change in one of the delays τ_{1i}.

Since the optimization procedure stops at the minimum closest to the start values, and the quasi-period of 0.07 ns is smaller than the uncertainty associated with the start values, it was necessary to add a routine to the optimization procedure to ensure that the global minimum was found. Various strategies have been implemented in that routine, but after some experimentation it was found possible to choose a strategy that yielded in a few central processing unit (CPU) seconds the global minimum and then the multipath parameters for one sweep from a sequence of sweeps. The CPU time used to analyze the first sweep of a sequence is usually several minutes long, depending on the complexity of the measured sweep patterns. A detailed description of the strategies and their application are given in [23].

IV. RESULTS

Measurements performed in the evening of August 19, 1974, resulted in signal levels that were sometimes 60 dB below the normal daytime level. Fig. 5 displays the maximum and the minimum values of the received signal level observed within each sweep during the time interval from 23:25 to 23:56 h. The difference between the maximum and the minimum signal level was 18 dB at 23:25 h, indicating that within the experiments sweep range frequency selective fadings had occurred at that time. This difference of maximum and minimum signal levels decreased to a few decibels in 30 s and remained almost constant until 23:34 h. In the period of constant difference the maximum level changed about 8 dB, which may imply that multipath propagation occurred during this period but that the frequency selective fading minima were outside the sweep range.

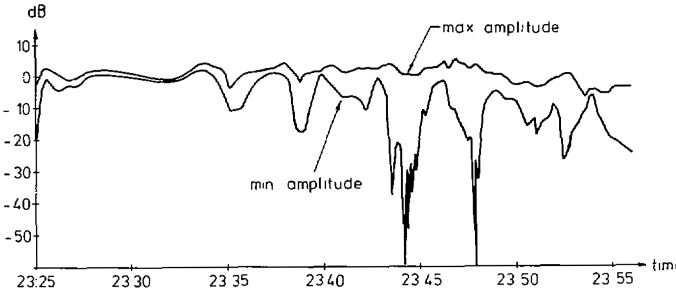

Fig. 5. Maximum and minimum values of received signal level in sweeps recorded from 23:25–23:55 h on August 19, 1974.

Around 23:34 h the minimum signal level became unstable and showed changes of tens of decibels during half a minute, whereas the maximum level changed by less than 5 dB during the same period. From 23:43 h to 23:45 h the instability of the minimum signal level was particularly pronounced, and the minimum level reached was −60 dB at 23:44:12 h.

The sweep patterns for the unstable period have been analyzed by means of the method outlined in Section III. Fig. 6 shows the resulting fit for a typical sweep. The points marked with a "diamond" are measured values, while the curves synthesized by using the multipath parameters presented in Table I are unmarked. The figure displays excellent fitting except for phase, which deviates by a constant slope from the synthesized curve. This deviation arises because in place of the computed phase curve the measured differential phase curve is used for the fitting, attaching weight to matching the spikes of that curve. The deviation can be remedied by changing all the delays by an additive constant. This has not been done because only differences in delays are found. The test quantity

$$\sum_{n=1}^{516} F(\bar{x}, f_n)^2 + G(\bar{x}, f_n)^2 \tag{9}$$

is small (1.628) and gives a mean relative error of four percent for the amplitude fit and a mean absolute error of 0.04 rad for the differential phase fit.

Experience has shown that only the first two terms of the series expansion in (7) need to be included, and since the terms a_{11} and a_{12} are one order of magnitude smaller than a_{01} and a_{02}, the propagation conditions have been rather stable during the 331-ms sweep time. This comment applies to the whole period except for the sweeps around 23:44:30 h and around 23:47 h, for which the minimum level in Fig. 5 shows fast changes.

Figs. 7–10 display the values of $a_{01}, a_{02}, a_{03}, (\tau_{12} - \tau_{11})$ found for the period shown in Fig. 5. The scale in Fig. 9 has been expanded ten times with respect to the scales in Figs. 7 and 8. Since the amplitude of the third path is only one-tenth of the amplitude on the first and second paths, the question could arise as to whether the third path is a physical reality or a consequence of the rounding off errors in the computational process. To resolve this problem, consider Fig. 11, which shows the difference $a_{01} - a_{02}$ as being less than a_{03} around the times with deep fadings. (At a fading minimum the sum of the two main paths is about $a_{01} - a_{02}$.) This and the fact that the test quantity in (9) increased one order of magnitude when the third path was removed strongly indicate that the third path is a physical reality.

Common to Figs. 7–11 is the slow change in multipath

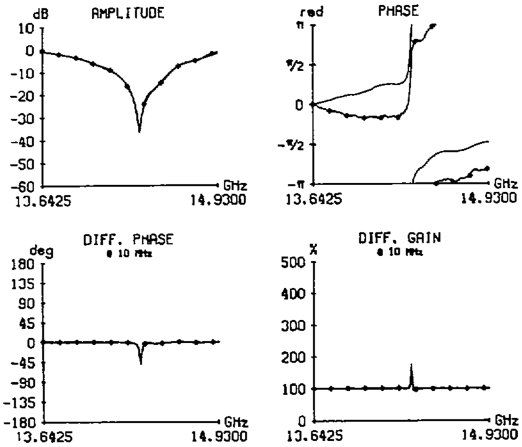

Fig. 6. Set of matched patterns. Multipath parameters are presented in Table I.

TABLE I
THE RESULTING MULTIPATH PARAMETERS OF THE MATCH IN FIG. 6

i	a_{0i}	a_{1i}	τ_{0i}	$\tau_{1i} - \tau_{11}$
1	0.5439	-0.0253	0.00	0.00
2	0.5297	0.0727	0.09	0.44
3	0.0197	0.0253	-0.02	3.53

The phase term τ_{0i} is in fractions of 2π rad, and the delay $\tau_{1i} - \tau_{11}$ is in nanoseconds.

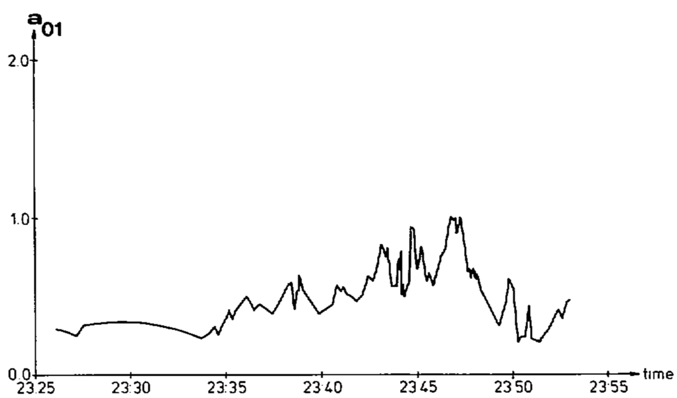

Fig. 7. Amplitude term a_{01}.

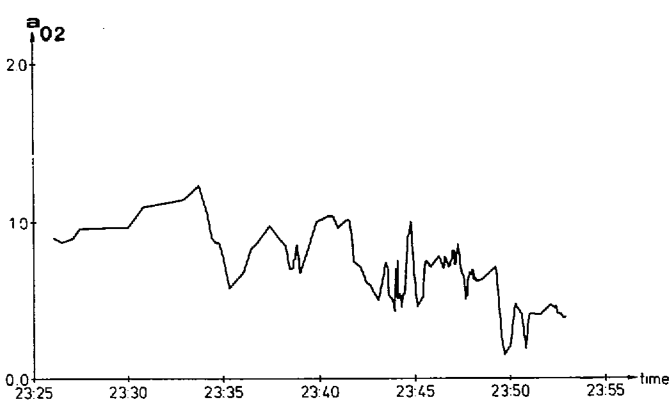

Fig. 8. Amplitude term a_{02}.

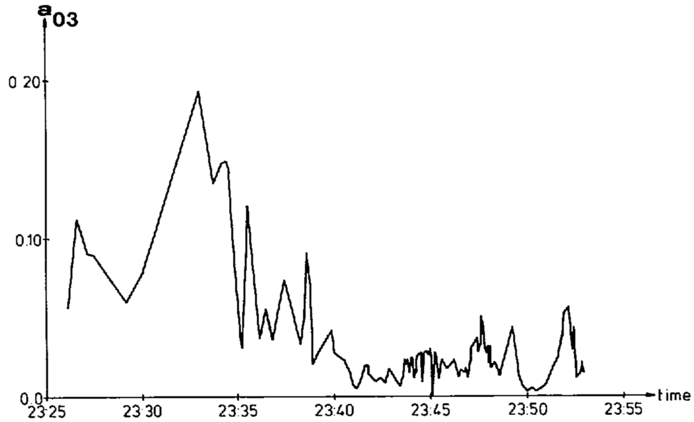

Fig. 9. Amplitude term a_{03}.

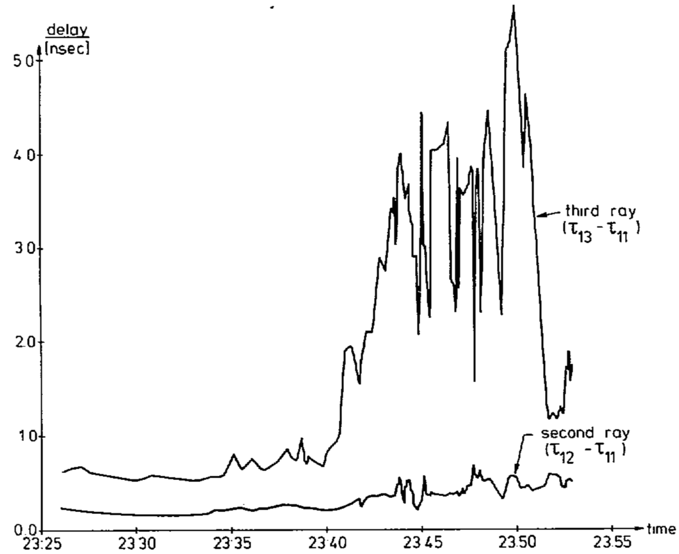

Fig. 10. Relative delays $\tau_{12} - \tau_{11}$ and $\tau_{13} - \tau_{11}$ of second and third rays in nanoseconds.

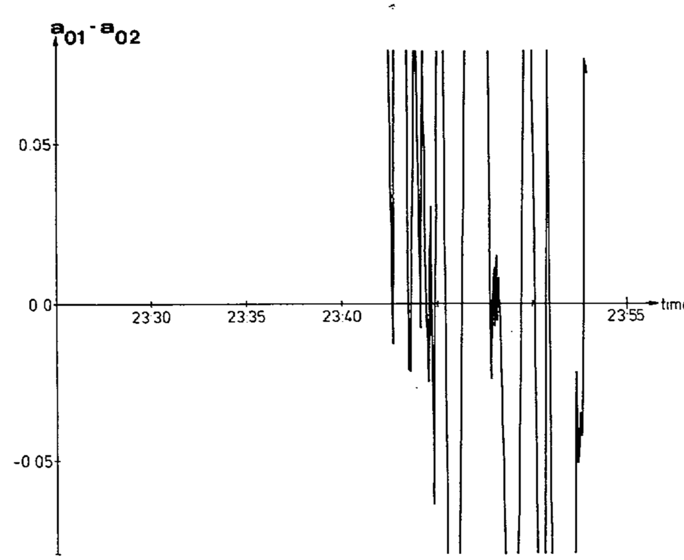

Fig. 11. Difference $a_{01} - a_{02}$.

parameters between 23:25 h and 23:40 h. When fast changes in the minimum signal level occurred (see Fig. 6), the multipath parameters changed rapidly, with the first path being sometimes stronger than the second ($a_{01} > a_{02}$) and sometimes vice versa. This confirms the occurrence of changes in the layer structure of the troposphere, with typical time constants of about 1 s [25].

On the average, one sweep required 108 s of CPU time on an IBM 370/165, and the mean value of the test quantity obtained from (9) was 1.14. Fig. 12 shows a fit of a sweep with complicated patterns. The fit is rather good and the test quantity obtained from (9) is 5.15. As expected, it was necessary to include some of the time (frequency) dependent terms of (7) to obtain a good fit. The terms are presented in Table II.

To investigate the accuracy obtainable with the analysis procedure that has been outlined, a sweep with a single fading of 40 dB was analyzed by using completely different starting values in the optimization procedure. This resulted in the three sets of multipath parameters shown in Table III. A coarse measure of the absolute accuracy of the amplitude a_{0i} and the delay $(\tau_{1i} - \tau_{11})$ of the propagation paths with the greatest amplitudes is 0.1 and 0.3 ns, respectively. It is noted that the differences in $(\tau_{1i} - \tau_{11})$ from set to set are multiples of the quasi-period of 0.7 ns.

V. CONCLUSION

A computer program which can find the multipath parameters on the basis of measured amplitude and differential phase patterns has been developed, and the capabilities of the program have been demonstrated. Hitherto, such analyses of swept measured amplitude patterns have been performed with the aid of analog simulators.

The CPU time required to analyze a sweep on an IBM 370/165 digital computer was, on the average, 108 s, based on 160 sweeps in total. By refining the strategies of finding the global minimum of the object functions, the average CPU time was reduced to 15 s/sweep.

In some cases it has been found necessary to include the time variation of the propagation medium during the 331-ms sweep in order to obtain trustworthy multipath parameters. The obtainable accuracy of the multipath parameters is estimated to be about 0.3 ns in delay and 0.1 in amplitude.

No propagation conditions requiring more than four paths have been met, but in some cases it was necessary to allow for appreciable time variations of the multipath parameters during the sweep. Ruthroff [14] has stated that three time varying paths should be sufficient to describe any propagation situation, but he assumes that only one refracting layer exists in the troposphere.

Rummler [27] has recently presented a fixed multipath model consisting of three paths. He assumes that the relative delay of the second path is much smaller than that of the third path, and he finds that the amplitude of the third path is much smaller than the amplitudes of the other paths. This is in good agreement with the results presented here.

The automatic analysis, the possibility of including the time variation of the propagation medium during the sweep, and the measure of how well the patterns synthesized on the basis of the resulting multipath parameters fit the measured patterns, combine to make this computerized analysis preferable to any hand-served analog simulator analysis. It is believed that the computerized analysis is capable of yielding more precise multipath parameters faster than previous methods.

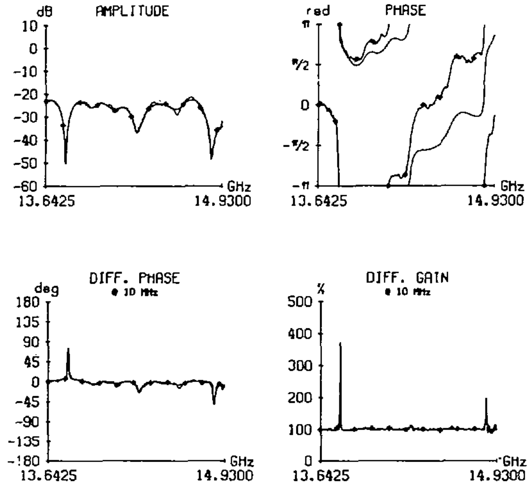

Fig. 12. Match of complicated sweep patterns.

TABLE II
THE RESULTING MULTIPATH PARAMETERS OF THE MATCH IN FIG. 12

i	a_{0i}	a_{1i}	a_{2i}	τ_{0i}	$\tau_{1i}-\tau_{11}$	τ_{2i}	τ_{3i}
1	0.0401	0.0029	0.0471	0.00	0.00	-0.45	-0.06
2	0.0124	0.0220	0.0942	-0.06	2.26	0.84	-0.86
3	0.0135	0.0133	-0.0050	-0.86	0.44	0.34	2.71
4	0.0020	-0.0087	0.0378	2.71	0.88	0.28	0.89

The phase term τ_{0i} is in fractions of 2π rad, and the delay $\tau_{1i} - \tau_{11}$ is in nanoseconds.

TABLE III
RESULTING MULTIPATH PARAMETERS OF THE SAME SWEEP WHEN USING DIFFERENT START VALUES IN THE OPTIMIZATION PROCEDURE

Set	Test Quantity	i	a_{0i}	a_{1i}	τ_{0i}	$\tau_{1i}-\tau_{11}$
1	1.63	1	0.5439	-0.0253	0.00	0.00
		2	0.5297	0.0727	0.09	0.44
		3	0.0197	0.0253	-0.02	3.53
2	2.03	1	0.4757	-0.0900	0.00	0.00
		2	0.4653	0.0905	0.11	0.72
		3	0.0182	0.0234	0.20	2.55
3	5.12	1	0.3739	0.0919	0.00	0.00
		2	0.3667	-0.1000	0.19	0.51
		3	0.0305	0.0302	0.18	3.52

The phase term τ_{0i} is in fractions of 2π rad, and the delay $\tau_{1i} - \tau_{11}$ is in nanoseconds. Set 1 is equal to Table I.

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REFERENCES

[1] B. R. Bean and E. J. Dutton, *Radio Meteorology*. New York: Dover, 1968, pp. 49–88.

[2] D. C. Livingston, *The Physics of Microwave Propagation*. Englewood Cliffs, NJ: Prentice Hall, 1970.

[3] J. Grosskopf, "Wellenausbreitung I", "Wellenausbreitung II", *Hochschultaschenbucher*, Bibliographisches Institute No. 141 + 141 a and No. 539/539 a, Mannheim 1970 (in German).

[4] L. B. Felsen and G. M. Whitman, "Wave propagation in time-varying media," *IEEE Trans. Antennas Propagat.*, vol. AP-18, pp. 242–253, Mar. 1970.

[5] S. Choudhary and L. B. Felsen, "Asymptotic theory for inhomogenous waves," *IEEE Trans. Antennas Propagat.*, vol. AP-21, pp. 827–842, Nov. 1973.

[6] K. A. Connor and L. B. Felsen, "Complex space-time rays and their application to pulse propagation in lossy dispersive media," *Proc. IEEE*, vol. 62, pp. 1586–1598, Nov. 1974.

[7] O. E. DeLange, "Propagation studies at microwave frequencies by means of very short pulses," *Bell Syst. Tech. J.*, vol. 31, pp. 91–103, Jan. 1952.

[8] A. Bernardini, G. Di Blasio, P. Mandarini, and G. F. Meucci, "Channel model and experimental evaluation of its parameters by direct observation of the impulse response for a line-of-sight radio link," presented at the URSI Commission F Conf. on Propagation in Non-Ionized Media, La Baule, France, Apr. 28–May 6, 1977, pp. 459–462.

[9] A. B. Crawford and W. C. Jakes, "Selective fading of microwaves," *Bell Syst. Tech. J.*, vol. 31, pp. 68–90, Jan. 1952.

[10] R. L. Kaylor, "A statistical study of selective fading of super high frequency radio signals," *Bell Syst. Tech. J.*, vol. 32, pp. 1187–1202, Sept. 1953.

[11] R. W. Meadows, R. E. Lindgren, and J. C. Samuel, "Measurement of multipath propagation over a line-of-sight radio link at 4 GHz using frequency-sweep techniques," *Proc. Inst. Elec. Eng.*, vol. 113, pp. 41–48, Jan. 1966.

[12] D. Turner, B. J. Easterbrook, and J. E. Golding, "Experimental investigation into radio propagation at 11.0–11.5 GHz," *Proc. Inst. Elec. Eng.*, vol. 113, pp. 1477–1489, Sept. 1966.

[13] R. L. O. Tattersall, B. C. Barnes, and N. E. Cartwright, "Multipath transmission tests at 11, 20 and 37 GHz," in *Conf. Proc. on Propagation of Radio Waves at Frequencies above 10 GHz*, Savoy Place, London WC2, England, Apr. 10–13, 1973.

[14] C. L. Ruthroff, "Multiple-path fading on line-of-sight microwave radio systems as a function of path length and frequency," *Bell Syst. Tech. J.*, vol. 50, pp. 2375–2398, Sept. 1971.

[15] W. M. Sharpless, "Measurement of the angle of arrival of microwaves," *Proc. IRE*, vol. 34, pp. 837–845, Nov. 1946.

[16] A. B. Crawford and W. M. Sharpless, "Further observations of the angle of arrival of microwaves," *Proc. IRE*, vol. 34, pp. 845–848, Nov. 1946.

[17] E. Lintz Christensen, "13.5–15.0 GHz sweep amplitude and phase propagation measurements," in *Int. Symp. Problems of Space and Terrestrial Microwave Propagation*, Austria 1975, ESA publ. SP 113, pp. 257–263.

[18] G. E. Mogensen, "Experimental investigation of radio wave propagation in the 13.5–15.0 GHz frequency band," Electromagnet. Inst., Tech. Univ. Denmark, Publ. No. LD30, Apr. 1977.

[19] E. Lintz Christensen and G. Mogensen, "Experimental investigation of line-of-sight propagation at 13.5–15.0 GHz," *Radio and Electron. Eng. (GB)*, vol. 49, pp. 127–140, Mar. 1979.

[20] ——, "13.5–15 GHz line-of-sigh experiment," presented at the URSI Commission F Conf. on Propagation in Non-Ionized Media, La Baule, France, Apr. 28–May 6, 1977, pp. 447–452.

[21] G. Mogensen and E. Lintz Christensen, "Fading and intermodulation-noise statistics from a 14 GHz L.O.S. propagation experiment," presented at the URSI Commission F Conf. on Propagation in Non-Ionized Media, La Baule, France, Apr. 28–May 6, 1977, pp. 453–458.

[22] E. T. Stephansen and G. E. Mogensen, "Experimental investigation of some effects of multipath propagation on a line-of-sight path at 14 GHz," *IEEE Trans. Commun.*, vol. COM-27, pp. 643–647, Mar. 1979.

[23] J. Sandberg, "Multipath parameters and multipath propagation related to PSK communication," Ph.D. dissertation, Electromagnet. Inst., Tech. Univ. Denmark, publ. No. LD34, June 1978.

[24] ——, "Multipath parameters from swept measurements," presented at the URSI Commission F Conf. on Propagation in Non-Ionized Media," La Baule, France, Apr. 28–May 6, 1977, pp. 441–446.

[25] J. A. Saxton, J. A. Lane, R. W. Meadows, and P. A. Matthews, "Layer structure of the troposphere," *Proc. Inst. Elec. Eng.*, vol. 111, pp. 275–283, Feb. 1964.

[26] L. J. Greenstein, "A multipath fading channel model for terrestrial digital radio systems," *IEEE Trans. Commun.*, vol. COM-26, pp. 1247–1250, Aug. 1978.

[27] W. D. Rummler, "A new selective fading model: Application to propagation data," *Bell Syst. Tech. J.*, vol. 58, pp. 1037–1071, May–June 1979.

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